CATALYZING A SUSTAINABLE RENAISSANCE OF AMERICAN MINING

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It’s time to wake up!!
What am I going to talk about?

‣ A bit about ARPA-E

‣ A peek into the abyss

‣ A look at white spaces for those who are not faint of heart

https://elements.visualcapitalist.com/a-lifetimes-consumption-of-fossil-fuels-visualized/
Most importantly

‣ I’m here to start a conversation
‣ I don’t have the answers
‣ But do know
  – Business as usual won’t cut it and
  – My generation isn’t going to solve the problem
‣ I’m looking for your bold suggestions

Btw - This is not an official view of the DOE or ARPA-E

It’s time to wake up!!
Who, what and how do we fund?

Who?
- Academics, big companies, small companies, National Labs

What?
- Transformative projects

How?
- CRADAs through programs
- Grants through special topics
- SBIR/STTR (we call SEED)
THE ABYSS
The Last 8 Years Have Been the Warmest on Record

Global land and ocean surface temperature anomalies (degrees Celsius compared to the 20th century average)

Global mean surface temperature from 1901-2000

- Land: 8.5°C
- Sea: 16.1°C
- Land & Sea: 13.9°C

2022: +0.86°C*

* 2022 figure refers to the temperature anomaly for January through September
Source: NOAA
Couldul T depend on $[\text{CO}_2]$?
CO$_2$ and 2ºC

*Note:* This is a national scenario consistent with an at least 66 percent chance of limiting global warming to below 2°C. Some residual gross greenhouse gas emissions (both CO$_2$ and non-CO$_2$) will remain at the end of the century even with ambitious climate action because they are too difficult or costly to remove entirely. Once negative emissions exceed those that remain net zero emissions is reached.

*Source:* Adapted from a visual in The UNEP Gap Report 2017 (Figure 72)
We have the Tech for Clean Energy
So, what’s wrong?

It’s time to wake up!!
In the Beginning...

There are mountains and rocks

Then comes everything for the energy transition
We need to move “from BIG Oil to BIG Shovels"

— Daniel Yergin
Metals required for EV’s and Clean Energy

Globally
>1,000,000,000 cars
>400,000,000 trucks

Global Energy Use
170,000 TWh

Another Challenge: will hydrogen meet the moment?

Today

70 Mt per year

1.5% global emissions

2% global primary energy
Overhauling an entire industry in 30 years...

Hydrogen Demand Sectors

- Existing Uses
- New Uses

1/5 global CO₂ emissions to be stored for blue hydrogen

> 3 TW renewable energy capacity for green hydrogen

+ basically all of the platinum group metals we know of

Some might say "why can't we just dig more?"

- Easy stuff has been mined
- Ore is lower quality
- Local & regional ecosystem fragility
- Community willingness to host
- Societal avoidance of resource extraction
- ... and demand for resource-rich technology
The US Not a Player

Manganese 100%
Rare Earths 100%
Vanadium 94%
Cobalt 78%
Magnesium 52%

>90% of base metal is imported

Nickel 47% of class 1 nickel is imported
Lithium 25% *100% of battery grade

Maximum US Reliance on Oil/Gas Imports
Was 30% in 2005

USGS 2021 Mineral Commodity Summaries 2021 (usgs.gov)
From Simon Michaux - GTK

Remember, this is for just the first generation of units. They will wear out in 10 to 25 years, after which they will need to be replaced.
Mining – How much are we talking about?

The world produced roughly 2.8 billion tonnes of metals in 2021. Here are all the metals we mined, visualized on the same scale.

**INDUSTRIAL METALS**
181,579,892 tonnes

**TECHNOLOGY AND PRECIOUS METALS**
1,474,889 tonnes

**LARGEST END-USE**
- Steelmaking
- Construction
- Energy/Batteries
- Magnets
- Electronics
- Other

Source: Visual Capitalist Commodity Summaries (2023)
*Production does not reflect actual metal production as metals only make up a certain portion of ore.
**Steel/Irrefy production.
***Represents lithium ion concentrate production.
How much do we have to dig?

The metal we want

Tailings and Slags

Unprocessed waste rock

Concentration in processed ore

[Cu] - < 1%
[Ni] - < 1%
[PGE] - < 10 ppm
[Gold] - < 10 ppm
How much do we dig for our metals?

Tailings are what is left over after economic minerals are separated from mined rock. They comprise ground rock material and liquid waste from mineral processing plants.

They are fine particles mixed with water, forming a slurry that is stored in ponds or dams. The volume of tailings and their storage pose a risk to the natural and human environment.

The Global Tailings Review estimates that the total number active, inactive and closed storage facilities is 8,500 with 217km$^2$ of tailings, enough to fill a cube 6km high.

They produce more tailings than others. The type, quality, quantity and production decisions of mineral deposits determine the amount of tailings waste a specific mine produces.

1 Bt of Cu = 100+Bt of ore = 99+ Bt of tailings and ?? Bt of waste rock

THE FUTURE
What do we need to do?

▸ Just doing more of the same is not an option
  – Environmental impact
  – Ore bodies
  – No social license

▸ What the future must deal with?
  – Environment
    • GHG footprint of mining
    • Dealing with wastes
  – Economy
    • High energy usage
    • Use low quality ores
  – Society
Leveraging Accelerated CO₂ Mineralization

*Note this is an active ARPA-E program*
Mineralization is a Natural Process that Sequesters CO$_2$

Nature’s way takes WAY TOO MUCH time – literally eons

- Basically reaction of ambient CO$_2$ and water with rocks
- Locks CO2 away as stable carbonates

http://butane.chem.uiuc.edu/pshapley/Environmental/L29/2.html
How Improved Element Extraction Will be Accomplished

- Convert components of low-grade ores containing ER elements from harder to process forms to easier forms
- Easier mineral classification and beneficiation
- Reduced energy needs
- Different chemical pathway(s) for element liberation
- Potential additional products

**Demonstrative reactions in olivine ore...**

\[
\begin{align*}
\text{Mg}_2\text{SiO}_4 &+ 2\text{CO}_2 & \rightarrow & \text{NiX} + [\text{byproducts}] \\
\text{NiSiO}_3 &+ \text{CO}_2 & \rightarrow & 2\text{MgCO}_3 + \text{SiO}_2
\end{align*}
\]

NiX = ferro nickel (35% Ni, 65% Fe), nickel oxides (NiO), pure nickel. NiO thermodynamically favorable over NiCO₃.
MINER Summary

Program Goals:

• Develop net GHGe negative technologies that utilize the reactive potential of CO\textsubscript{2}-reactive ore bodies
• While decreasing comminution energy and
• Increase the domestic supplies of critical metals

Increase Beneficiation Efficiency

Carbonates are easier to grind

Increase Metals

Gigatons of metals from CO\textsubscript{2}-reactive minerals

Ex. olivine

(Mg, Fe, Ni)\textsubscript{2}SiO\textsubscript{4}

Modeling

Carbonation, critical metal, and storage potential

Carbon Sequestration

Gigatons of stable CO\textsubscript{2} storage potential
MINER Summary (cont’d): Ex. of Net Negative Process Flows

Example: In Situ
- Excavate Ore
- Carbonate Ore
- Increase metals
- Decrease comminution
- Carbonate ore in subsurface
- Mineral Beneficiation
- Excavate carbonated ore

Example: Ex Situ
- Excavate Ore
- Carbonate ore
- Increase metals
- Decrease comminution
- Carbonate ore post-excavation
- Mineral Beneficiation
Impact of Carbonation

- Improved operations
  - Comminution
  - Mineral recovery

- Sequestration of CO$_2$ = Scope1/2/3

- Stabilization of process waste

https://pubs.rsc.org/en/content/articlelanding/2013/ra/c3ra44007a
Valorizing Everything that is Extracted
Perhaps take hike to a tailings pile?

What is in the tailings pile?

For Cu – typically Ca/Mg/Fe/Al/Si

All stuff that is mined somewhere else
We need methods for mineral fractionation

- All of the elements in a tailings pile are mined elsewhere

- Can you imagine treating it like an oil refinery? Valorizing every atom and molecule

- If we stack value, like a refinery, does it release the full value?
Impact of Using Everything

- No tailings
- Not digging another hole for something that is recovered
- Stacking of value to maximize return from the operations
Precision In-situ Mining
Inspiration from Laparoscopic and Arthroscopic Surgery

**Laparoscopy** - a surgical procedure in which a fiber-optic instrument is inserted through the abdominal wall to view the organs in the abdomen or to permit a surgical procedure.

**Arthroscopy** (ahr-THROS-kuh-pee) is a procedure for diagnosing and treating joint problems. A surgeon inserts a narrow tube attached to a fiber-optic video camera through a small incision — about the size of a buttonhole. The view inside your joint is transmitted to a high-definition video monitor.
Drill down to ore body and remove only what one wants

- Drill down to the ore of interest
  - *Btw, you need to know where it is...*
- Remove the metal
  - In situ leach or
  - Dissolve and pull or
  - Mechanically pulverize

No more digging – a new environmentally friendly way of mining

MAY 16, 2021

A more elaborate approach
From Doug Hollett
US DOE
Private Communication
Impact of Precision Extraction

- No removal of overburden
- No big hole to be filled
- No humans in the subsurface
- Minimized impact on aquifers
Harnessing Geologic Hydrogen
Maybe you should be interested in Old Faithful?

- High concentrations of H₂ found in Yellowstone thermal zones
- Geyser water is basically saturated with H₂. Higher concentrations in the head space.
- Diverse community of hydrogen consuming extremophiles
Whence Hydrogen from the Earth

- Very complex chemical cycles
- Both Fe(II) oxidative and radioactive sources in play
- This fits conventional wisdom that high pressure and temperatures required.
Geologic Hydrogen

>2.6 x 10^{15} \text{ tons H}_2 \text{ Potential}

H_2 \text{ resources likely “infinite” relative to human usage.}

Reservoirs could be explored and potentially stimulated to produce zero-emissions H_2 \text{ in-situ.}

1: Larin 1993
2: Zgonnik 2020
3: Moretti et al., 2021
Example: In-situ Mineralization

Serpentinization Basics

- Serpentinitization occurs in mafic-ultramafic rock
  - The most common rock type in earth’s crust
- Ultramafic rocks have low Si activity, and the activity of oxygen is prevented from dropping to very low values by the fayalite (olivine)-magnetite-quartz buffer
- Under these conditions water is capable of oxidizing Fe$^{2+}$:

  \[
  3\text{Fe}^{2+}\text{SiO}_4 + 3\text{H}_2\text{O} \rightarrow 2\text{Fe}^{3+}\text{Fe}^{2+}\text{O}_4 + 3\text{SiO}_2 + 2\text{H}_2
  \]

Geologic Cross-Section of Anthropogenic In-Situ Serpentinitization

- Reservoir rock (before stimulation)
- Olivine (Mg, Fe$^{2+}$)SiO$_4$ + pyroxene (Mg, Fe$^{3+}$)$_2$SiO$_6$

Reservoir Conditions

- Reducing conditions
- ~200 °C
- ~10 MPa
So, why connect $H_2$ to mining?

- Well, it involves rocks
- Avoids mining other things
  - Platinum Group Elements
  - Materials for $e^-$ generation
  - Materials for the grid+storage
- GeoH2 is a primary fuel NOT an energy carrier.
What else is needed to solve this massive problem?

- Finding what’s in the ground
- Drilling deep, fast and cheap
- Deep earth engineering
- Ability to fracture rock with accuracy
- Water management techniques!!!!
  - Water-free processes?
- Mine restoration/remediation
- And much more
So, what are your bold solutions?

“The climate system is an angry beast and we are poking it with sticks.”

Wallace “Wally” Smith Broecker was one of the first ones to raise warnings on climate change and popularized the term “Global Warming”. He was also one of the masterminds behind the Carbfix project.

It’s time to wake up!!